Practical Use of the Building Debris Hazard Prediction Model, DISPRE

by

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ABSTRACT

Final validation of the first version of the building debris hazard prediction model DISPRE was completed in 1990. The model was developed for the U.S. Department of Energy (DOE) and was approved as an acceptable siting tool by the U.S. Department of Defense Explosives Safety Board (DDESB) in November 1990. It was verified and refined using data from an extensive component test program. The data from these tests were used to validate the model for analyzing explosives operations buildings constructed of one or more of the following components: reinforced concrete, masonry (clay tiles or concrete masonry units), or lightweight components such as corrugated metal. Since the DDESB approval of DISPRE, its use by both DOE and Department of Defense (DoD) contractors has continued to increase. In this paper, the analysis of an example building will be presented in a step-by-step manner to illustrate how the model can be used to safely site explosives handling or processing facilities. It is important to note that the DISPRE model does not replace, but supplements, the existing broad-ranged DoD 6055.9-STD hazardous debris siting criteria, i.e. the model is recognized as an approved alternative analysis method which can be exercised to reduce the required inhabited building distance for a particular site. The complete model procedure is described in DDESB Technical Paper No. 13, April 1991.

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1.0 Introduction

A model has recently been developed to predict safe siting distance for protection from hazardous building debris which can result from an accidental detonation within a structure. Version 1.0 of this model (called "DISPRE" for dispersion prediction) has been validated for providing conservative distance predictions using data from an extensive component test program. In November 1990, the DISPRE model was approved for use as a siting tool by the Department of Energy (DOE) and the Department of Defense Explosives Safety Board (DDESB). Since its verification and approval, DISPRE has been widely used to assess potential debris hazards at a variety of explosives handling and processing facilities. Common usage includes analyzing buildings to determine safety criteria compliance, providing backup analysis for requesting safety exemptions, or determining safe positions for new structures.

The major concentration of this paper is an illustration of a typical building analysis. A single building is analyzed using two different explosive charge locations to demonstrate the importance of accurately defining the worst case charge location for use in the analysis. The analyst must choose a realistic location and not just the closest distance to a component if explosives are not likely to be initiated in that location. The results of each step in the procedure are presented, and the final siting distances are compared to the default inhabited building distances quoted in DoD 6055.9-STD (Reference 1). In addition to the presentation of the example building analysis, several upcoming improvements to the model are discussed, along with recommended future enhancements.

2.0 General Description of DISPRE Model

DISPRE is a procedure which can be used to determine proper siting distance between explosive handling structures and inhabited buildings to prevent both personnel and building exposure to hazardous building debris. The model is a combination of steps which involve the use of computer codes and prescribed intermediate calculations based on analysis of test data. The three computer codes in the model are SHOCK (Reference 2), FRANG (Reference 3), and MUDEMIMP (Reference 4). Version 1.0 of both SHOCK and FRANG, as obtained from the Naval Civil Engineering Laboratory (NCEL), is used in the current model. Version 1.1 (or later) of the MUDEMIMP code should be used. This code has undergone significant modifications based on data from the large component test program associated with the development and refinement of DISPRE. The intermediate calculations establish input for the computer codes.

The procedural steps of the model progress through the following general tasks:

- prediction of internal loads, including shock and gas load contributions,
- component breakup prediction and calculation of debris characteristics (such as mass, velocity, drag, and angle),

- determination of debris trajectories and dispersion, and
- consideration of debris tumble after initial impact (roll and ricochet).

General overviews of each of these tasks are given in this section. Brief descriptions of the actual steps used to make the predictions are provided in Section 3.0. To use the model, one needs to refer to the detailed steps presented in DDESB Technical Paper No. 13 (Reference 5) or the final report for the refinement project sponsored by DOE (Reference 6). Reference 6 provides more detailed information on the creation of the model and the test program used to obtain validation data, and it includes complete documentation of the refinement of the model based on the test data.

2.1 Prediction of Internal Loads

Blast loading inside a confined space can be characterized by an initial shock phase which is usually followed by a gas or quasistatic phase loading. The shock phase consists of very short duration, high pressure pulses which load surfaces as the shock reverberates within the donor bay. The magnitude of the shock phase depends on the charge amount, the distance to the loaded surface, and the location of nearby reflecting surfaces. The magnitude and duration of the quasistatic phase depend on the charge amount, the donor bay volume, and the available vent area and mass of vent covers. If the vent area is sufficiently large and the vent cover mass is small, the gas phase is essentially eliminated.

Two types of shock loading are considered by the model -- close-in and far-range loading. Close-in loading occurs when the charge is so close to the component that the applied pressures locally overwhelm its strength. The component loses all structural integrity, and the maximum wall motion is determined by the maximum applied impulse. Far-range loading occurs when the charge is far enough from the wall so that basic structural integrity is maintained, and the wall responds to an average, more uniform load. The use of model procedures for determining close-in loading is limited to situations where the scaled standoff between the charge and the component is between 0.5 and 1.0 $ft/lb^{1/3}$. All greater standoffs are considered far-range shock loading.

The SHOCK and FRANG computer codes are used to determine the shock and gas impulse on all components in a donor structure. A combination of the impulse predicted using both codes is used to calculate maximum debris velocity (and several other debris characteristics related to velocity) for debris resulting from each loading realm discussed in this section. The model procedures prove to be an accurate treatment of the load based on comparisons to the test data listed in Reference 6. SHOCK is used to predict average shock phase loading on internal surfaces including the shock reflections off nearby surfaces. The program includes a reduced area option which allows determination of average shock impulse over a portion of a wall surface or at a single point on the wall. Thus, loads over the entire component, over a local area, or at a point directly across from the charge can be determined. Any gas impulse caused by a detonation in a confined building is predicted using the computer code FRANG.

2.2 Building Component Breakup and Debris Characteristics

Component breakup is predicted based on the applied load and the component type. A given debris piece can be described by an initial velocity, mass, vertical launch angle, and drag characteristics during flight. The distribution of each of these parameters for a given accident can be defined in terms of a probability density function. High speed film coverage and post-test data collection used in the DISPRE validation test program provided data to use in establishing the particular distribution function to use with each parameter. The breakup is predicted to provide input in a form compatible with the MUDEMIMP computer code used to estimate debris dispersion in the model. The choice of input probability distribution to use for each parameter is based on statistical correlations with test data. The specific recommended distributions for each parameter for each material covered by the model are summarized in Section 3.0, with more detailed descriptions provided in References 5 and 6.

2.3 Determination of Debris Dispersion

A modified version (Version 1.1 or later) of the MUDEMIMP code (Reference 4) for Multiple Debris Missile Impact Simulation is used to determine the hazardous debris distance and debris dispersion for a building. The results of the component breakup and debris characteristics prediction are used to create input for the MUDEMIMP code. Originally written by Louis Huang at the Naval Civil Engineering Laboratory (NCEL), this code uses a probabilistic approach to include variations and uncertainties of launch/flight characteristics of each individual debris missile from an explosion. It uses the Monte-Carlo random sampling technique to select a set of launch/flight parameters for each debris piece. It then calculates the trajectory, impact range, and terminal kinetic energy of each piece based on the selected initial conditions. In addition to an output file containing all input and output parameters for every debris missile simulated, the code also outputs a file containing cumulative hazardous debris density data. Hazardous debris are defined as those debris with impact kinetic energies exceeding a critical energy input by the user, e.g. 58 ft-lbs. Significant modifications to the original code which were made during the refinement of DISPRE are discussed in detail in Reference 6.

Five main launch/flight parameters are required to run the code: debris mass, initial velocity, initial trajectory angle, drag coefficient, and drag area factor. The actual input to the code is in the form of probability distributions which describe the possible range of values for each major parameter. Parameters for each individual debris piece are chosen by the code randomly selecting from the probability distributions. The probability density functions recommended for the five main launch/flight parameters for each of the materials covered by the model are summarized in Section 3.0.

The selected distributions are recommended based on extensive statistical sampling of the data from concrete and masonry tests conducted for this program. Other input includes initial height of debris and characteristic length. All debris are assumed to be launched from a single point. Refer to References 5 and 6 for a more complete description of the input.

2.4 Debris Tumble After Impact

If debris thrown from an explosion impacts the ground at a shallow angle, it will ricochet or roll after impact. Predicting the first impact location as the final resting place is very inaccurate and unconservative. Logic to calculate debris ricochet and roll distances from curve fits to test data is incorporated in Version 1.1 of the MUDEMIMP code. The test data include tests on masonry and concrete walls from both severe close-in loading and severe gas loading. The curve fits are discussed in detail in Reference 6. According to the roll and ricochet logic built into the code, the total debris throw distance is the sum of the distance to the first impact and the roll distance. The roll distance is calculated from the debris angle and velocity at first impact. Debris angle is only considered to the extent that debris with an impact angle less than 55 degrees from the horizontal are assumed to roll, whereas those debris impacting at higher angles are assumed not to roll. The debris impact velocity is used with curve fits from validation test data (Reference 6) and other data (References 7 and 8) to calculate the roll distance. The model will differentiate between concrete roll (roll of debris with three-dimensional breakup) and masonry roll (roll of debris with two-dimensional breakup).

No curve fits of debris roll were developed for lightweight wall debris or beams. There are not enough data available to develop curve fits. Initial attempts to predict measured debris distances for tests of these materials, assuming no roll, significantly underpredicted the measured distances. Predictions were also made assuming roll similar to that of masonry. These predictions compared conservatively to measured debris distances. Therefore, dispersion of all debris which exhibits two-dimensional breakup, i.e. breakup which does not include any fracture through the beam thickness, should be predicted assuming debris roll according to the curve fit developed for masonry. Breakup of light walls and beams is assumed to be two-dimensional breakup.

3.0 Summary of Step-by-Step Procedure

Detailed guidelines for using DISPRE to determine safe siting distance for a building are provided in References 5 and 6. Brief descriptions of the procedure steps are included here as a reference for the example building analysis presented in the following section.

1. *Define the threat.* Describe all structural components and the explosive charge and location. For siting purposes, the charge location should be a plausible location which would result in the worst case debris formation -- the key word is "plausible". As will be seen in the example analysis, charge location significantly affects debris density in any given direction.

2. *Determine vent areas and descriptions.* Define both covered and open vent areas and the panel weight per unit area of the covered areas.

3. *Calculate the impulse load on each component.* Both shock and gas loads are determined since both can contribute to the initial velocity at which debris will leave a building. First, the shock load is calculated using the SHOCK code. The area over which the shock load is applied to a component depends on how well the component is expected to distribute the load. Two types of component response can occur: local or global response. Local response occurs when the component has little strength compared to the applied load. For this type of response, the shock impulse is calculated at a point on the component opposite the explosive charge. Local response is considered for close-in loading of reinforced concrete and for all unreinforced masonry, plaster, and cement asbestos components. Global response results if a component is expected to maintain its integrity and respond to an average impulse over an area (which could be a reduced area of the component opposite the charge or the entire component). This type of response applies to far-range loading of reinforced concrete and to any loading of metal panels or steel beams.

   The gas impulse is calculated using the FRANG code. One or both of two types of venting are considered: venting through the area of the wall or roof with the least mass per unit area, or venting through the breached portion of the wall nearest the charge which is thrown out very quickly by the shock pressures. The type of venting which will govern for a particular component depends on the loading realm for the component and the mass per unit area of the other components (which surface will vent most quickly). The FRANG code calculates an initial gas pressure based on the ratio of the charge weight to the building volume. The code then steps through time, recalculating pressure and impulse at each time step. The pressure decreases as the vent area increases, i.e. as the vent panel moves outward. A critical vent time is marked at which the vent area equals the original vent opening area and the gas pressures in the building are assumed to no longer accelerate the vent panel or debris. The gas impulse at this critical vent time is used if the component being analyzed is a venting component. Non-venting components are exposed to the total gas impulse.

4. *Calculate the maximum debris velocity expected.* The basic form of the velocity calculation is

$$i_T/m$$

   where i_T is the total specific impulse for a particular component, which is the sum of the relevant shock and gas impulse. The parameter m is the mass per unit area of the component. The relevant shock impulse equals the impulse determined by the

SHOCK code, except for cases with close-in loading from a relatively small charge against a relatively thick concrete or masonry wall. In these special cases, the shock impulse is reduced using a curve fit to test data.

Velocities of steel beams and similar components are determined based on velocity predictions for constrained secondary fragments (Reference 6).

Since velocities of all debris, except steel beams, are assumed to be normally distributed, an average (or mean) velocity and a standard deviation of the velocity are calculated to define the distribution for the MUDEMIMP code.

5. *Calculate the average debris weight.* The empirically based equations for average debris weight, m_{avg}, are in the form shown below for concrete and masonry debris. The weight is converted to a mass within the MUDEMIMP code. For steel beams, the debris is considered to be the entire beam with a mass equal to the beam mass. For lightweight metal panels, the mass is assumed to be uniformly distributed between the values of one quarter panel and one full panel mass.

$$m_{avg} = M' \text{ (volume) (density)}$$

where M' is a factor based on fits to data.

6. *Determine the effective destroyed weight of the component.* The main use of this input by the MUDEMIMP code is to help define the input mass distribution and establish the adjustment factor to get the appropriate number of debris (as adjusted from the 5000 simulations required to obtain accurate parameter distributions). The effective destroyed mass is determined as follows:

   Total effective destroyed mass = T' (total component weight)

   where the component is the wall or roof being analyzed and T' is based on curve fits to data.

7. *Calculate the destroyed width, GRIDL, of the component.* Assume a circular destroyed area equal to the total effective destroyed mass divided by the component weight per unit area.

$$\text{GRIDL} = \sqrt{((4/\pi)\,(\textit{total effective destroyed mass})/(\textit{weight per unit area}))}$$

8. *Run MUDEMIMP to determine the hazardous debris distance.* The main input parameters are summarized in Table 1. Other key parameters and further descriptions of all the required variables are found in References 5 and 6.

Table 1. MUDEMIMP Input for Key Debris Parameters

Parameter	Density Function	Limits
Mass	Exponential for concrete and masonry Uniform for lightweight metal panels Constant for beams	m_{avg} m_{min}, m_{max} total beam mass
Total Mass	No distribution	total effective destroyed mass
Initial Velocity	Normal Constant for beams	mean = $V_{avg} = 0.6(V_{max})$ sd* = $V_{std} = 0.14(V_{max})$ V_{max}
Initial Trajectory Angle	Normal Constant for beams	mean = the normal to the surface measured relative to the horizontal sd* = 1.3 or 10 degrees angle = the normal to the surface measured relative to the horizontal
Drag Area Factor	Constant	1.0
Drag Coefficient (3-dimensional breakup) Drag Coefficient (2-dimensional breakup) Drag Coefficient (beams)	Uniform Constant Constant	1.0, 2.0 1.5 1.8

* sd = standard deviation

sd = 1.3 degrees
(a) close-in loading of concrete, masonry, and plaster components
(b) far-range loading of masonry and plaster components
(c) far-range loading of concrete components not restrained by the roof

sd = 10 degrees
(a) all loading of corrugated metal components
(b) far-range loading of concrete walls restrained at the roof
(c) all roofs

9. *Obtain pertinent information from the program output files.* The model is run for each component of a building. The number of hazardous debris in a certain direction will be the graphical sum of the number of hazardous debris from the wall components facing that direction and half of the roof hazardous debris. Half of the roof debris are used since potentially half of these debris could contribute to the hazard in a particular direction.

4.0 Example Building Analysis

To illustrate the use of the DISPRE model, an example siting analysis of a building constructed of common materials (for which the model has been verified) is presented in this section. Results are summarized for each step in the procedure for two analyzed cases as described in Step 1.

Step 1: *Define the threat.*

The building, shown in Figure 1, is 20 ft x 20 ft x 12 ft high. It has three 12-in. thick reinforced concrete walls, one unreinforced masonry wall, and a roof composed of metal panels, 5-ply felt, and gravel. The metal panels have a 4 ft width and are 20 ft in length. The panels are supported by open web steel joists spaced at 4 ft on center. The weight per unit area of the metal panels is 2 lb/ft^2. The weight per unit area of the built-up roof (felt and gravel) is 6 lb/ft^2. The weight per unit area of the roof system is then 8 lb/ft^2. A hollow steel door is centered in the unreinforced masonry front wall. The door weight per unit area, considering the cover plates and internal stiffeners, is 5.6 lb/ft^2.

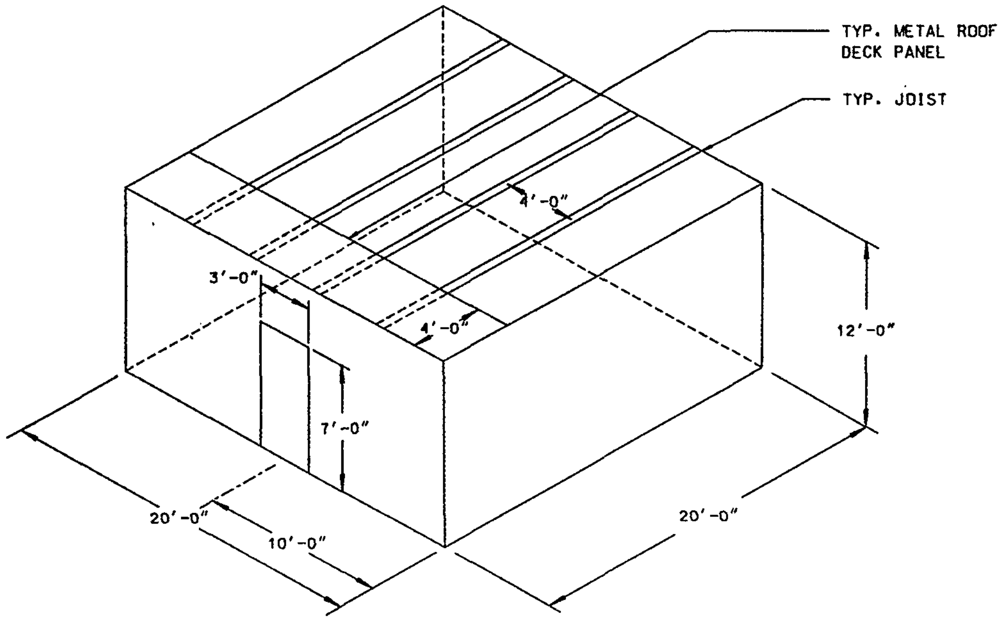

Figure 1. Sketch of Example Building

A bare spherical charge equivalent to 50 lb TNT is assumed. Two cases have been analyzed, with all parameters the same for each case except the charge location. For Case 1, the charge can be located anywhere within a designated high explosives (HE) area which has boundaries 3 ft from each wall as shown in Figure 2. The minimum height off the floor is 2 ft.

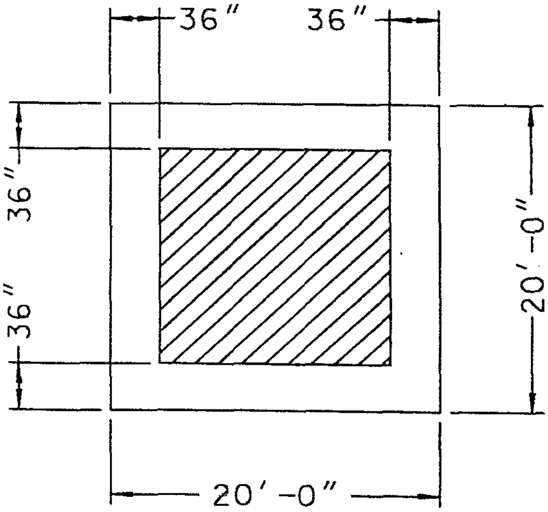

Figure 2. Designated HE Area for Case 1

Case 2 considers a fixed charge location in the center of the building, representing the position of fixed processing or testing equipment. The height off the floor is 4 ft. The loaded surfaces for both cases are defined below:

Surface 1	12 ft x 20 ft clay tile wall
Surface 2	12 ft x 20 ft reinforced concrete wall
Surface 3	12 ft x 20 ft reinforced concrete wall
Surface 4	12 ft x 20 ft reinforced concrete wall
Surface 5	20 ft x 20 ft metal panel roof with 5-ply felt and gravel
Surface 6	steel joist in roof
Surface 7	3 ft x 7 ft steel door in clay tile wall

Step 2: *Determine the vent areas and descriptions.*

Two covered vent areas are considered for the example building for both cases -- the roof and the steel door. There are no open vent areas to be input to the FRANG code. A summary of the vent panel characteristics is shown in Table 2. The door consists of two 16 gauge steel cover plates (with two inch spacing) and internal stiffners.

Table 2. Summary of Vent Characteristics for FRANG Input

Vent	Covered Vent Area (ft^2)	Weight/Area (lb/ft^2)	Vent Perimeter (ft)	Total Panel Weight (lb)
Steel Door	21	5.6	20	117
Metal Roof	400	8.0	80	3200

Step 3: *Calculate the impulse load on each component.*

The shock impulse and gas impulse loads on each surface or component are summarized in Table 3 for Cases 1 and 2. Since the charge location for Case 2 is fixed in the center of the room, the shock impulse is considerably less severe for the walls and door. The shock loads on the roof panels and joists do not vary greatly since the distance from the charge to these parameters only changed from 10 ft to 8 ft between Cases 1 and 2 (the Case 1 charge height is 2 ft off the floor while the Case 2 height is 4 ft). The gas impulse loads for all but the clay tile wall (Surface 1) and the door (Surface 7) do not vary significantly. The gas loads on the clay tile wall and the door are affected by the charge location for several reasons. These components are lighter in weight than the reinforced concrete walls and will vent more quickly with the closer charge location in Case 1. The quicker venting of these components results in less gas impulse for the clay tile wall and the door for Case 1. As with the shock impulse, the gas impulse load on the metal roof does not change much since the distance from the charge to the roof is almost the same for the two cases. The model does not apply a gas load to the steel roof joists since the panels supported by the joists will break away much sooner than the joists (if the joists break away at all), and most of the gas pressure will be vented through the openings created by the failed metal panels.

Step 4: *Calculate the maximum debris velocity for each component.*

As decribed in Section 3.0 and in References 5 and 6, this step involves four calculations: relevant shock impulse, total relevant impulse, maximum debris velocity, and the mean and standard deviation of the normal velocity distribution. The results of these calculations are summarized in Tables 4 and 5.

Table 3. Summary of Impulse Loads

Surface	Description	Shock Impulse (psi-sec)		Gas Impulse (psi-sec)	
		Case 1	Case 2	Case 1	Case 2
1	12 ft x 20 ft clay tile wall	1.9	0.60	0.60	0.99
2-4	12 ft x 20 ft reinforced concrete walls	1.9	0.47	1.0	0.99
5	20 ft x 20 ft metal roof	0.41	0.40	0.86	0.85
6	steel joist in roof	0.42	0.39	0.0	0.0
7	steel door	1.2	0.55	0.10	0.19

Table 4. Intermediate Load Calculations

Surface	Description	Relevant Shock Impulse (psi-sec)		Total Impulse (psi-sec)	
		Case 1	Case 2	Case 1	Case 2
1	12 ft x 20 ft clay tile wall	1.9	0.60	2.5	1.6
2-4	12 ft x 20 ft reinforced concrete walls	1.2	0.47	2.2	1.5
5	20 ft x 20 ft metal roof	0.41	0.40	1.3	1.2
6	steel joist in roof	0.42	0.39	0.42	0.39
7	steel door	1.2	0.55	1.3	0.74

Table 5. Debris Velocity Parameters

Surface	Description	Maximum Velocity (ft/sec)		Average Velocity (ft/sec)		Velocity Standard Deviation (ft/sec)	
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
1	12 ft x 20 ft clay tile wall	521	331	313	199	73	46
2-4	12 ft x 20 ft reinforced concrete walls	68	45	41	27	9.5	6.3
5	20 ft x 20 ft metal roof	730	719	438	431	102	101
6	steel joist in roof	no failure	no failure	--	--	--	--
7	steel door	1046	611	--	--	--	--

Since the loads on the walls and door are significantly decreased for the fixed charge location for Case 2, the maximum debris velocity calculated for these components is substantially less as well. For both Case 1 and 2, the steel joists in the roof are shown by calculations not to fail, so no further debris parameter calculations are necessary for the joists. It is also not necessary to calculate an average velocity and velocity standard deviation for the steel door since no distribution will be defined for the door. The door is treated as a single debris piece. The MUDEMIMP code is still used to determine its trajectory, but constant distributions (single values) are input for its key parameters.

Steps 5-7: *Calculate the average debris weight, the effective destroyed weight, and the destroyed width (for use in determining debris density) for each component.*

Table 6 summarizes the results of these calculations for Cases 1 and 2. Note the average debris weights for all components are not affected by the charge location for this building. The empirically based equations used to determine this parameter are average fits through the range of test data used to validate the model. Since both cases analyzed in this paper fall within the data range, the average weight is not affected by the charge location. The effective destroyed weight varies for the reinforced concrete walls because the velocities for the two cases lie within different regimes of the empirical equations (Reference 6). The destroyed width is determined directly from the effective destroyed weight, so the destroyed width for each component is the same for both cases, except the width for the reinforced concrete walls.

Table 6. Summary of Component Weights and Destroyed Widths

Surface	Description	Average Debris Weight (lb)		Effective Destroyed Weight (lb)		Destroyed Width (ft)	
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
1	12 ft x 20 ft clay tile wall	0.29	0.29	7920	7920	17.5	17.5
2-4	12 ft x 20 ft reinforced concrete walls	2.6	2.6	1800	3600	3.9	5.5
5	20 ft x 20 ft metal roof	m_{max}=160 m_{min}=40*	m_{max}=160 m_{min}=40*	800	800	20***	20***
7	steel door	117**	117**	117	117	20***	20***

* For metal panels, a maximum and minimum mass are needed to define the uniform distribution for mass.

** The door is treated as a single piece of debris.

*** The equation for calculating the destroyed width yields a number greater than the width of the building, so the building width is used.

Step 8: *Set up the input files and run the MUDEMIMP code for each component.*

Most of the key input for the MUDEMIMP code for each component has been summarized in Tables 2 through 6. The probability density functions to be used for mass, velocity, angle, drag coefficient, and drag area factor, along with other varying input are listed in Table 7. Reference 5 or 6 must be referenced for the input file format. The code results for maximum range and maximum cumulative hazardous distance are summarized in Table 8.

Table 7. Additional Input for the MUDEMIMP Code

Surface	Description	Mass (both cases)	Velocity (both cases)	Angle (both cases)	Drag Coefficient (both cases)	Drag Area Factor (both cases)	Initial Height, Y (ft)		Density (lb/ft^3)	Breakup Parameter (both cases)	Charact. Length (ft) (both cases)
							Case 1	Case 2			
1	12 ft x 20 ft clay tile wall	Exponent	Normal	Normal	Constant	Constant	2	4	120	2	0.0625
2-4	12 ft x 20 ft reinforced concrete walls	Exponent	Normal	Normal	Uniform	Constant	2	4	150	3	1
5	20 ft x 20 ft metal roof	Uniform	Normal	Normal	Constant	Constant	12	12	490	2	0.004
7	steel door	Constant	Constant	Constant	Constant	Constant	2	4	33	2	0.17

Table 8. Predicted Hazardous Debris Distance

Surface	Description	Maximum Range (ft)		Cumulative Hazardous Distance (ft)		Cumulative Hazardous Distance x 1.3 (ft)	
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
1	12 ft x 20 ft clay tile wall	770	479	761	479	989	623
2-4	12 ft x 20 ft reinforced concrete walls	132	76	131	74	170	96
5	20 ft x 20 ft metal roof	221	220	50	50	--	--
7	steel door	1011	696	--	--	--	--

A couple of items should be noted concerning the results displayed in Table 8 before discussing the implications of the results. Three distances are recorded for each component for both Case 1 and 2. The maximum distance is the maximum distance any single debris piece is expected to travel following an accidental detonation in the example building. The cumulative hazardous distance is the maximum distance at which to expect more than one hazardous debris per 600 square feet, where a hazardous debris is defined as one having kinetic energy upon impact equal to or greater than an input critical kinetic energy. Since DoD 6055.9-STD defines this critical kinetic energy as 58 ft-lbs, this is the value used as input in the MUDEMIMP code. The density in any particular direction is determined by counting the number of debris landing or passing through an area defined by a trapezoid with one base and height equal to the destroyed width of the component facing that direction. The third column shows the cumulative hazardous distance multiplied by a 1.3 safety factor. This factor is only applied to reinforced concrete or unreinforced masonry debris, such as the clay tile wall debris. The factor is applied to assure a 95% confidence level in the conservatism of the final predicted debris distance. It was derived using statistical analysis on the validation test data during model refinement. The factor accounts for scatter between the test data and curve fits, and the expected variation between accidents.

Step 9: *Make a siting recommendation based on the results for each direction from the structure.*

The default inhabited building distance separation for protection from hazardous debris for a 50 lb charge is 670 ft, as defined by DoD 6055.9-STD. For an actual building, one would conduct an analysis using the DISPRE model in order to possibly reduce this default distance to prove that an existing separation distance is safe or to save distance in siting a new facility. The analyst must examine the debris in each direction. The number of hazardous debris in any given direction will be the graphical sum of the number of hazardous debris from the wall components (and associated doors, windows, etc.) facing that direction and half the roof hazardous debris. The roof debris are generally distributed equally in four directions if the roof is flat, but the model can only distribute the debris in two dimensions. Thus, half the roof debris are used since potentially half these debris could contribute to the hazard in a particular direction.

One exception to the use of the cumulative hazardous debris distance in obtaining a graphical sum is the analysis of a building containing components constructed with steel beams or joists, or one including doors. The maximum debris distance predicted when making single debris runs with the MUDEMIMP code for these components should be compared to the hazardous debris distance predicted for other debris in a given direction. The greater distance of cumulative hazardous debris distance or maximum beam or door distance should set the siting distance in each direction.

The siting distance in the three directions out from the three reinforced concrete walls will be equal, so only two siting distances must be determined for this example -- one distance out from the clay tile wall and one distance out from any of the reinforced concrete walls. The example building/charge configurations analyzed for this paper were chosen mainly to illustrate the difference in debris dispersion for different charge locations within the same building, but the analysis also demonstrates some of the limits of the model and the conservatism built into the predicted results.

First, one should note the significant decrease in both the maximum range and cumulative hazardous debris distance for Case 2, with the charge fixed on a piece of equipment centered in the building. An analyst should always select the charge location producing the worst possible load, but considerable thought should be taken to make certain the location is a plausible one. If the charge will never equal the full maximum limit in one location, then the building should not be analyzed for that situation. Also, if the charge is only processed in a fixed location (such as assumed for Case 2 of this example), and the probability of accidental detonation in transit to that location is extremely small, no other location should be considered in the analysis.

For Case 1, with the charge located anywhere in the defined HE area, the maximum cumulative hazardous distance for the clay tile debris is 761 ft. The maximum range traveled by any of the roof debris is 221 ft, so the roof debris do not increase the hazardous debris distance of the wall debris in the direction of the clay tile wall. Applying the 1.3 safety factor for concrete and masonry debris, the siting distance based on wall debris would be 989 ft. However, the door travels 1011 ft, so the calculated siting distance would be 1011 ft unless a maze or some type of barricade

is constructed to stop the door. Presuming some measure would be taken to eliminate the door hazard, the predicted distance for clay tile wall debris still exceeds the default criteria of 670 ft. The default distance of 670 ft from DoD 6055.9-STD can be used if the distance predicted by the model exceeds 670 ft. No distance reduction is achieved for this direction, but distance is saved in the other three directions.

The cumulative hazardous debris distance from the reinforced concrete debris is 131 ft, which converts to 170 ft when the 1.3 safety factor is applied. Although the cumulative hazardous debris distance for the roof debris is 50 ft, the maximum distance traveled by the roof debris is 221 ft. The maximum debris range of concrete wall debris is (132 ft)(1.3) = 172 ft. The roof debris landing in or passing through the area up to 172 ft will contribute to the hazardous debris density. However, the roof debris traveling past 172 ft do not result in cumulative densities greater than one per 600 square feet. Thus, the debris safe siting distance in the directions out from the concrete walls is 172 ft, which is a significant reduction from the default distance of 670 ft for these directions.

For Case 2, with the charge fixed in the center of the building, the maximum cumulative hazardous debris distance for the clay tile wall debris is 479 ft. Applying the 1.3 safety factor, this distance is converted to 623 ft. The maximum range traveled by any roof debris is 220 ft, so the roof debris do not increase the hazardous debris distance of the wall debris. However, the door travels 696 ft in this direction, so a maze or barricade should be designed to stop the door from setting the siting distance. If the door can be stopped in this fashion, the safe debris siting distance in the direction of the clay tile front wall is 623 ft. Although this distance is not much less than the default distance of 670 ft, the separation distances in the other three directions can be even more significantly reduced than for Case 1.

The cumulative hazardous debris distance for reinforced concrete debris is (74 ft)(1.3) = 96 ft. The maximum distance traveled by concrete debris is (76 ft)(1.3) = 99 ft. The maximum cumulative hazardous distance of roof debris is 50 ft, but the maximum range of roof debris is 220 ft. The combination of roof and concrete wall debris would result in a cumulative hazardous distance of 99 ft, since some of the roof debris traveling past 50 ft could contribute to the hazardous debris density between 50 and 99 ft. Beyond 99 ft, there are only roof debris, and these debris do not result in hazardous densities. Thus, the safe debris siting distance out from any of the three reinforced concrete walls is 99 ft, a large reduction from the default distance of 670 ft.

In summary, the DISPRE model could be used to significantly reduce the separation distance between the example explosives processing building and adjacent inhabited buildings in three directions for either proposed charge location, especially for the centered charge location in Case 2. No reduction is gained for the fourth direction out from the clay tile wall. However, if this were an actual building, the clay tile wall may have been included as a "blow-out" wall intended to vent the building following an accident, along with the light metal roof. Clay tile may not usually be considered frangible, but when used with three reinforced concrete walls, it has much less weight

per unit area and, thus, can help vent the explosion products. If the wall is intended to vent, the building would be placed in a location such that the debris from this wall would not be thrown toward any other buildings or personnel in the complex.

5.0 Future Improvements in the Model

The DISPRE model has been used to analyze numerous buildings since the DDESB approval of the model in November 1990. In many instances, significant savings have been achieved by allowing reductions in building separation distances, without compromising safety of personnel or processing capability of a plant. The model has indeed been proven to be a useful siting tool. However, as with many empirically based models, DISPRE can and should be further refined. The model has been proven to provide conservative results for the reinforced concrete and masonry components on which the validation tests concentrated. It now needs to be exercised for more situations, including varied charge locations, components made of other common materials, and buried structures. Also, current limits of the model for charge weight and debris velocity are 250 lb of TNT equivalent explosives material and 1000 ft/sec, respectively. One exception to the velocity limit is in the analysis of metal panel components. The breakup of these components for explosive quantities less than 250 lb can result in velocities greater than 1000 ft/sec, so only the explosive quantity limit of 250 lb applies to metal panel components. More tests could be conducted in an effort to raise both the explosive quantity limit and the constraint on debris velocity. The analysis of structures used for explosives material storage typically requires consideration of explosive amounts in excess of 250 lb.

Additional tests and analysis need to be conducted for corrugated metal panel surfaces and other lightweight components since the model bases its current analysis of these components on two validation tests and data collected from limited accident data bases. No recommendations have been included, for instance, on analyzing wood walls, yet several situations have arisen in which an analyst needed to predict debris throw from this type of wall. The effects of close-in and far-range loading on lightweight components need to be studied in much more detail, as the loading has been shown to greatly affect the manner in which these components fail and the size of the resultant debris.

Another key area of additional analysis should be a more detailed study of the 1.3 safety factor. This factor was developed based on a statistical analysis of the ratio of predicted maximum debris distance to measured maximum debris distance for 22 reinforced concrete and unreinforced masonry tests. Of these 22 tests, 8 maximum distances were underpredicted (resulted in a ratio less than 1.0). A safety factor of 1.3 applied to each of the 8 data points was statistically examined. The distance ratios were fit to a Weibull distribution to determine the certainty with which the model will produce conservative results. However, the 14 tests for which distances were conservatively predicted were not included in the distribution. The results of the analysis were that one could be

95% confident that only 11.6% of the predicted maximum distance values would be less than the corresponding actual distance values. A safety factor less than 1.3 may produce an acceptable confidence level if a more detailed statistical analysis is conducted.

The prediction of debris roll in the model should be expanded to include roll for higher velocities since the limit of the data used to derive the roll was about 120 ft/sec. In addition, the roll of debris of material types other than reinforced concrete and masonry needs to be examined with tests and analysis. In the DISPRE validation test program (Reference 6), roll was observed for metal panel debris, for instance, but the metal panel tests did not provide enough data to formulate a separate roll equation for these debris. Use of the masonry debris roll equations for metal panel and other lightweight components does produce conservative final distance predictions, but the predictions may be overly conservative in many instances. The roll equations for masonry have been used to predict final distance for data from accidents and other tests as well. These predictions also appear to be quite conservative. Further data specifically on roll of debris made of other common materials need to be obtained through controlled testing.

Although the DISPRE model has specific usage limits based on the verification data for parameters such as explosive quantity, initial debris velocity, and debris material type, it is, in many cases, the only methodology available and is extrapolated to cover situations outside the limits. Any extrapolation of DISPRE or modification to the step-by-step method must currently be done using good engineering judgment and with appropriate caution. For example, if accurate input distributions for fragment launch/flight parameters can be defined for primary fragments or equipment pieces, the MUDEMIMP code can be used to determine the trajectories and cumulative densities for these fragments as well as building debris. Some effort has also been devoted recently to establishing loads and trajectories to modify the procedure for use in analyzing buried structures. Since few methods exist for establishing fragment and debris densities with confidence to enable safe siting of buildings, DISPRE is frequently modified to cover situations outside its validation range. For this reason, refinement of the model in any or all of the areas described herein is highly recommended.

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